DEPARTMENT OF THE ARMY CORPS OF ENGINEERS

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

LONGSHORE-BARS AND LONGSHORE-TROUGHS

TECHNICAL MEMORANDUM NO. 15

LONGSHORE-BARS AND LONGSHORE-TROUGHS

TECHNICAL MEMORANDUM NO. 15
BEACH EROSION BOARD
CORPS OF ENGINEERS

JANUARY, 1950

Contribution from the Scripps Institution of Oceanography, New Series, No. 454

FOREWORD

This paper was prepared by Dr. Francis P. Shepard of the Scripps Institution of Oceanography and represents in part the results of research carried out for the U. S. Navy and the Beach Erosion Board. The report first appeared in limited issue as Submarine Geology Report No. 6 of the Scripps Institution of Oceanography, University of California. It is believed that the findings of the investigations are of sufficient value to merit publication at this time.

The opinions and conclusions expressed by the author are not necessarily those of the Board.

The authority for publication of this report was granted by an Act for the improvement and protection of beaches along the shores of the United States, Public Law No. 166, Seventy-ninth Congress, approved July 31, 1945.

TABLE OF CONTENTS

LONGSHORE-BARS AND LONGSHORE TROUGHS

Abstract

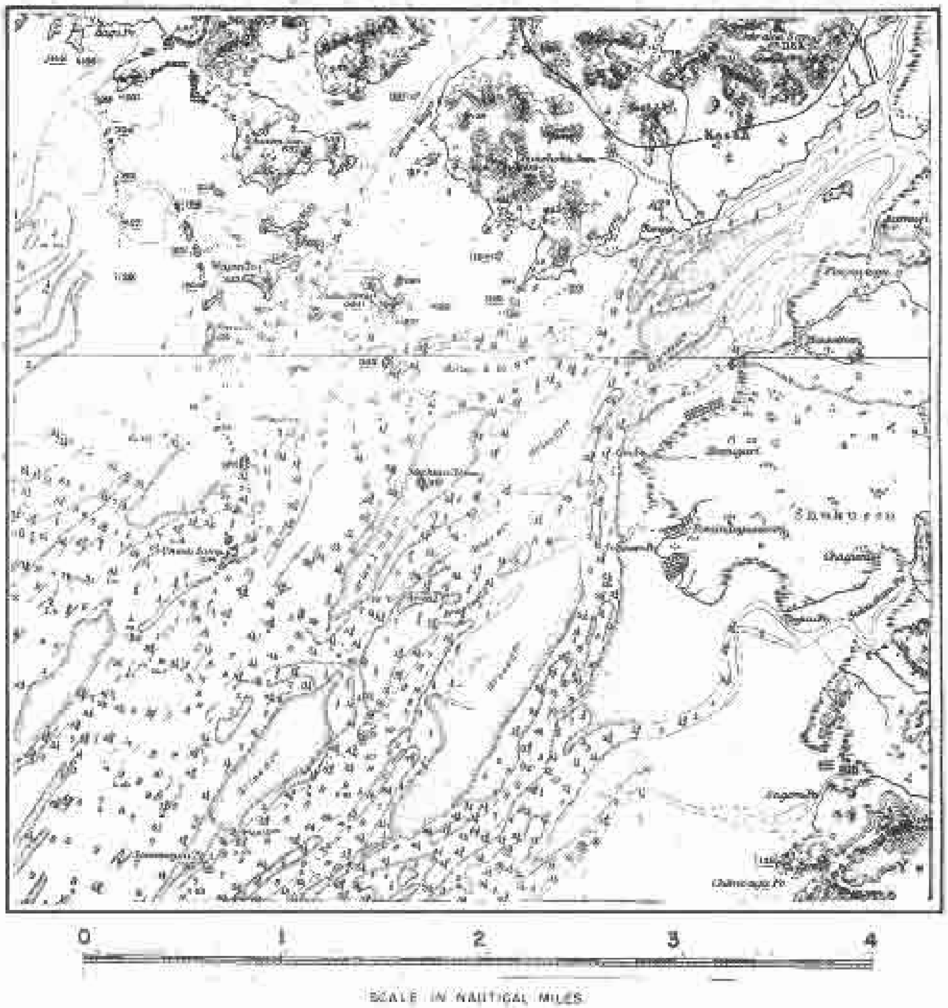
The submerged longshore-bars and longshore-troughs which skirt the shores off most sandy beaches are described. The troughs which lie landward of the bars are explained as the result of plunging breakers and the longshore currents which are feeders to rip currents. The bars are thought to be partly the result of the excavation of the troughs and partly due to landward migration of sand outside the breakers and seaward migration from the troughs. The depths of the bars and troughs are shown to be related to wave and breaker heights. The elimination of some bars is seen to be the effect of a long continued period of small waves during which the bar moves landward filling the trough. In many areas the deeper bars persist undisturbed through long periods of quiet seas. The analysis of thousands of profiles, mostly taken along California open ocean piers, is the chief basis for the preceding conclusions.

Introduction

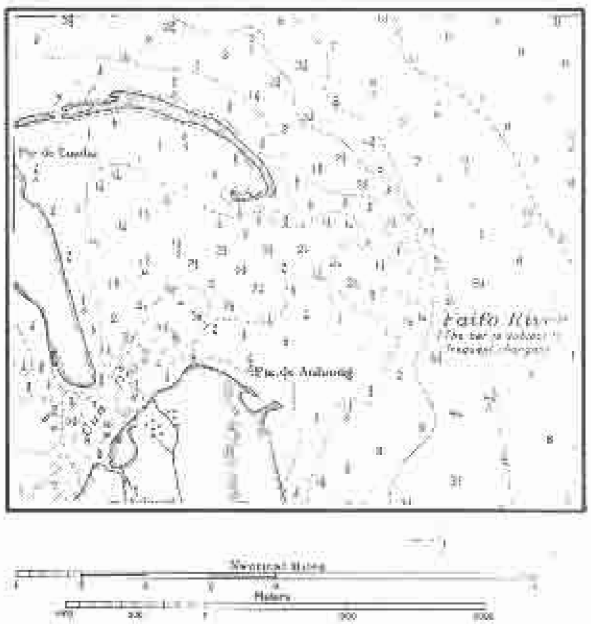
Because of their instability, submerged sand bars are a source of navigational difficulty to every type of craft from row boats to ocean liners. There appear to be three principal types of these shifting sand bars. One is crescentic in shape and is found off many river mouths and narrow entrances to bays (figure 1A). A second type is oval in shape and occurs in groups of somewhat parallel dune-like masses. Many of these are elongate parallel to the sides of straits and estuaries where there are strong currents and where abundant sediment is available (figure 1B). Others are more irregularly distributed. The third type of bar is long and narrow, extending essentially parallel to the shore line along most long sand beaches. The present discussion will deal only with this third type. This type presumably includes the cusp-like bars which were reported by King and Williams (9, p.75) from the shallow water along the margin of bays in the Mediterranean. King and Williams refer to the latter as crescent bars but they are decidedly different from the large crescents off bay entrances and are apparently more akin to beach cusps.

The term ball has been used to describe these shore-skirting bars, and their accompanying troughs, found inside the bars, have been referred to as lows. However, the word ball implies a roundish protuberance rather than an elongate ridge and low suggests a basin or valley, so that it seems advisable to use the more descriptive terms bar and trough for which there is ample precedent. In order to distinguish this type of bar from other types which include emergent bar beaches, a qualifying adjective is suggested so that they will be termed here longshore bars and longshore troughs.

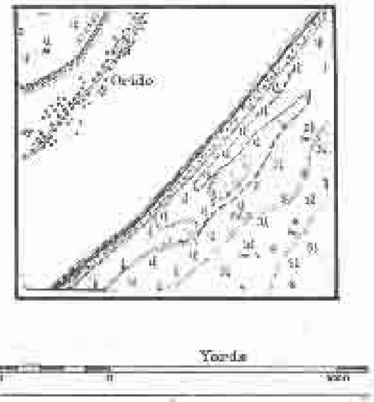
A.



B.



C.



THREE TYPES OF SUBMERGED SAND BARS

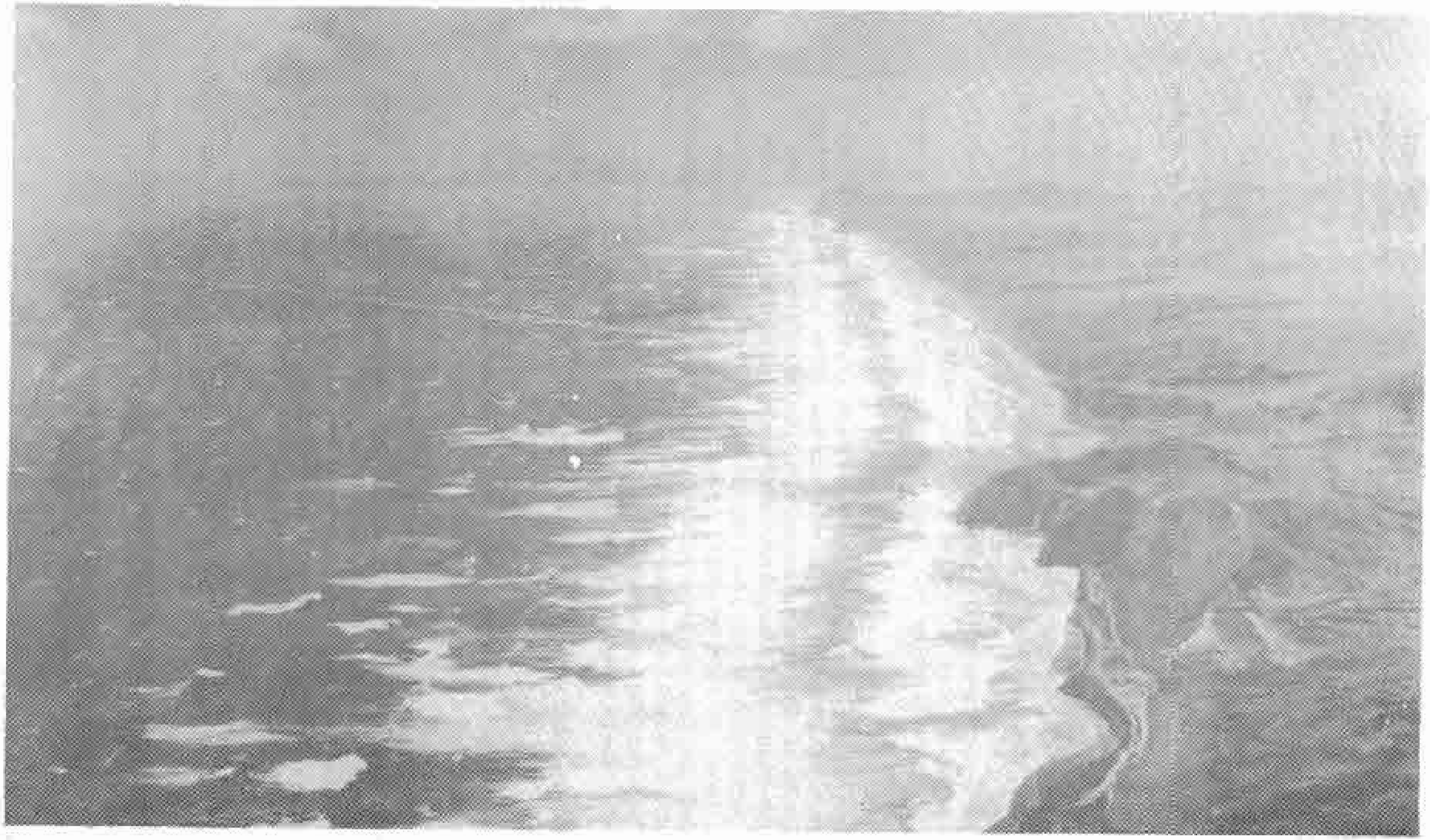
FIGURE 1

Anyone accustomed to surf swimming along relatively straight sandy beaches can hardly have failed to encounter the longshore-bars and troughs while wading out into the breakers. During periods of high waves the longshore-bars can be detected from any high place which commands a view of the surf zone, because the waves break along these shoal ridges (figure 2) and usually re-form on the inside breaking again either on inner longshore-bars or on the low tide terrace, a feature which is very common near the low tide level. If the water is clear during periods of small waves, the bars can be seen as variations in the color shading in the water along the shore.

Longshore-bars have been described by various authors, and suggestions have been made regarding their origin. A good summary of the earlier literature will be found in Johnson (6) and in Evans (2). A considerable number of profiles of the longshore-bars were made by German investigators, notably Otto (10) who studied a series of bars over a period of five years. Measurements by the U. S. Coast and Geodetic Survey (15) provided other information. Profiles of the longshore-bars of Lake Michigan were made by Evans who attempted also to determine the variation in position of these bars during one summer.

The work of Keulegan (6) with the Beach Erosion Board during and following World War II produced valuable wave-tank observations and an analysis of the mechanics involved in bar formation. Extensive field studies of longshore-bars were initiated during the war by the Department of Engineering of the University of California (Berkeley). Most of this material is not yet published although numerous profiles from various parts of the west coast have appeared as mimeographed laboratory memoranda from the Berkeley group. Important investigations were also conducted by King and Williams (9) which included field and tank observations.

At Scripps Institution information on longshore-bars has come particularly from daily measurements made along the 1,000-foot Institution pier during 1937 and 1938 (14) Subsequent measurements along this pier were made at various intervals, and profiles have been obtained along seven other California piers, all of which revealed the existence and the changing positions of bars. The pier profiles, particularly those made daily in 1937 and 1938, provide the greatest source of information for the present report since they contain the only available information on the changing depths and positions of the bars and troughs which can be definitely related to short period changes in waves, currents, tides, and winds. In a sense it is unfortunate that this information should come from pier profiles since piers form a sufficient obstruction both to waves and currents to set up special conditions. On the other hand nothing has as yet been developed to take the place of pier soundings for making accurate profiles through large breakers. Self-propelled sea sleds (4) may form an exception of this statment, but they have not been very successful. The breaker zone is the locus for bar and



AIR VIEW OF WAVES BREAKING ON LONGSHORE – BAR
ALONG WEST COAST NORTH ISLAND, NEW ZEALAND
(PHOTOGRAPH BY WHITES AVIATION, LTD., NEW ZEALAND)
FIGURE 2

trough development. Measurements with Dukws, the amphibious vehicles developed during the war, are fairly satisfactory during small-surf periods, but these periods are not as significant as large-wave periods. No records are available in which profiles were repeated at short intervals during which a daily check on sea conditions had been made.

Adequacy of Pier Profiles as a Source of Information

Since much of the information for the present discussion comes from pier profiles, some justification seems required of the use of this evidence from locations which are under special influences. Evans (2, p. 479) observed that the bars along the east shore of Lake Michigan were disturbed and broken up in the vicinity of piers. The piers tend to deflect longshore currents seaward as rip currents which in turn develop gaps in the bars. However, rip currents are not particularly common along Scripps pier. A much more common rip exists somewhat north of this pier. Furthermore the longshore-bars appear to be well developed along the piers of southern California and, so far as can be told from somewhat fragmentary information, do not appear to be particularly different from the bars on either side. As will be shown subsequently, the changes of bars and troughs have a definite relationship to wave and current conditions. Therefore it seems likely that the changes in the pier profiles are a fairly reliable index of what is happening on either side. Finally, the soundings were taken half way between piles where the least effect would occur and, in the case of the Scripps pier, a boom extended the sounding wire 10 feet outside the rail, further decreasing the piling influence.

If at some time in the future information becomes available from the slopes which are entirely free from pier influence, it will no doubt be more satisfactory. However, an enormous amount of difficult work must be accomplished before sufficient information is available to replace that coming from the thousands of pier profiles.

Characteristics of Longshore-bars and Longshore-troughs

King and Williams (9) express the opinion that the feature referred to here as a longshore-bar is typical only of "tideless seas" such as the Mediterranean and Baltic, and that another type which they call ridge and runnel is found exposed by low tide on beaches having large tidal ranges. The present investigations in areas where appreciable tidal ranges operate make this distinction seem of no great importance, although it may well be that the longshore-bars in the areas of large tidal range are less continuous and cut by more channels, partly as a result of runoff from the exposed troughs during low tide.

The study of the hundreds of west coast profiles shows a relationship between the depths of longshore-bars and longshore-troughs. If as suggested by Passarge (11) the longshore-bars are built by sediment thrown shoreward by the breaking waves, there should be excavation of a trough on the outside and building of a ridge on the inside of the

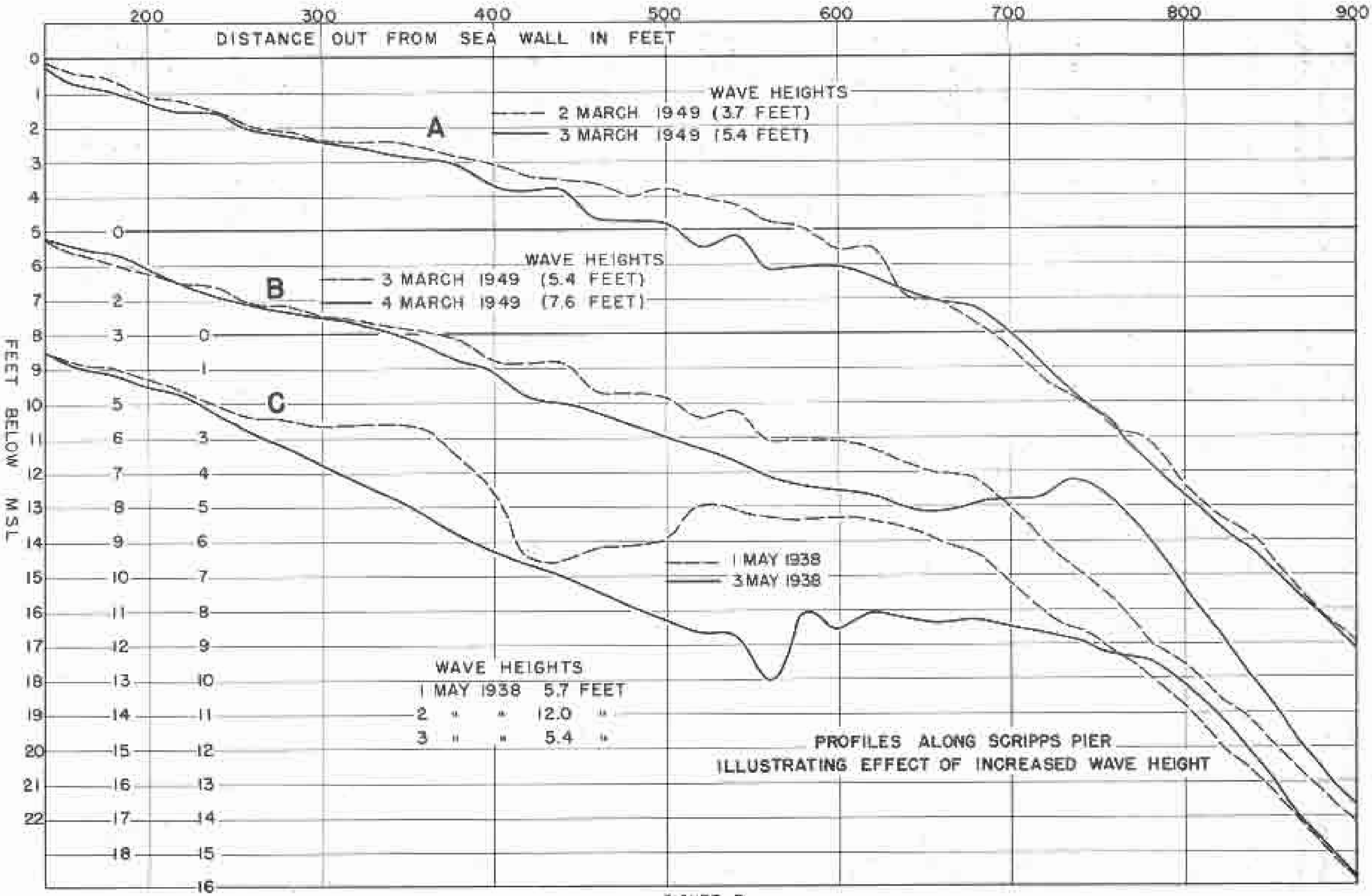
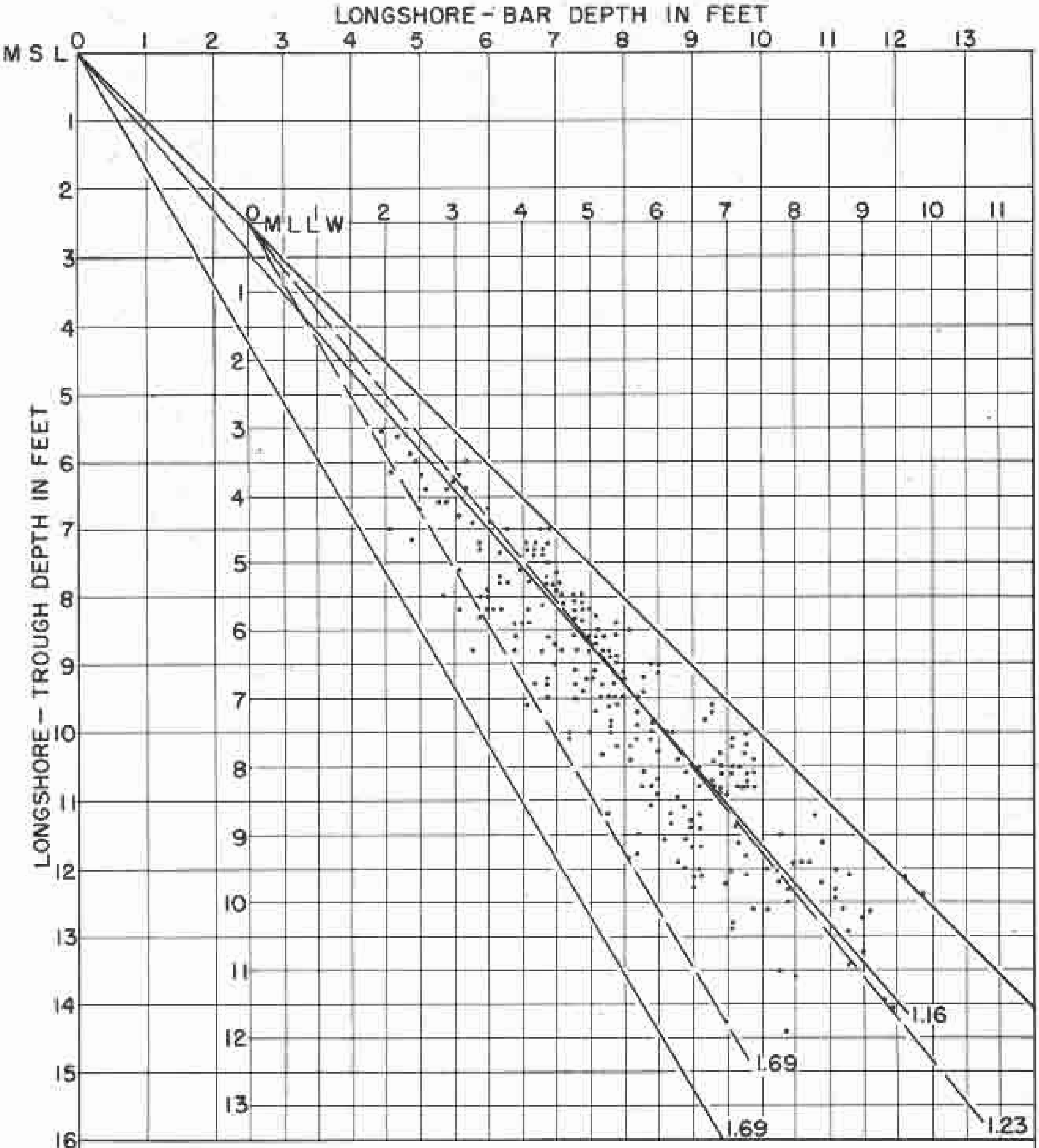

DISTANCE OUT FROM SEA WALL IN FEET
FEET BELOW MSL
WAVE HEIGHTS
2 MARCH 1949 (3.7 FEET)
3 MARCH 1949 (5.4 FEET)
A
WAVE HEIGHTS
3 MARCH 1949 (5.4 FEET)
4 MARCH 1949 (7.6 FEET)
B
C
1 MAY 1938
3 MAY 1938
WAVE HEIGHTS
1 MAY 1938 5.7 FEET
2 " " 12.0 "
3 " " 5.4 "
PROFILES ALONG SCRIPPS PIER
ILLUSTRATING EFFECT OF INCREASED WAVE HEIGHT

FIGURE 3

plunge point. A longshore-bar formed in this way should have a trough cut into the sand slope outside the bar, whereas the slope inside should remain essentially unchanged. Furthermore, the bars should form shoreward of the breaking waves. The daily profiles along the Scripps pier show that virtually all of the large longshore-bars form slightly seaward of the plunge points of the larger breakers occurring at the time the profile was measured. Furthermore, the trough is excavated on the inside and the bar is either left as an erosion remnant or is built up outside the trough (figures 3 and 18). This relationship is substantiated by the numerous cases where bars are found which have no concavity in the offshore slope outside and was suggested previously by Evans but without supporting evidence. It is also indicated in Keulegan's tank experiments.

Most profiles show more than one bar. In some places, as described by Evans (2) there are several parallel bars comparable in size and extending for many miles along the shore. Plane photos demonstrate such features along the shores of Texas, Louisiana, Lake Michigan, and Chesapeake Bay (8). The lines of breakers in plane photos showing the bars along other coasts indicate less continuous features and in many places suggest that only one significant bar exists. The pier profiles of southern California suggest that at least in this area one bar is much larger than any others which may exist. A count of the 1937-38 profiles at Scripps pier shows 209 with indications of one or more bars in addition to the large bar, whereas 90 profiles show only one bar. The remaining 54 profiles gave no indication of the existence of a bar. Evans found that in general the distance between the second and third longshore-bar is greater than that between the first and second, and that the bars grow successively deeper away from shore. This appears also to be true of most of the Oregon and Washington profiles reported by Isaacs (5). On the other hand no rule could be found relative to the plural longshore-bars measured along the Scripps pier. In a considerable number of cases the outer bar, which was the largest, stood higher than that directly inside.

Longshore-bars are very common off gently sloping sand beaches. So far as can be ascertained, steeply sloping beaches, that is, beaches where foreshore slopes are in excess of about 4°, have only very narrow insignificant bars. During the investigation of beach profiles in Oregon and Washington, Isaacs discovered that bars were not present in bays of small dimension. The report by King and Williams (9) of cusp-like bars in such localities is significant. The profiles suggest that longshore-bars and longshore-troughs do not exist outside of the zone where waves break during periods of high surf. However, so many of the sections establishing the existence of the bars terminate at depths near this outer limit that the statement may not be valid. Other types of submerged bars are known to exist at greater depth (16, chart V).



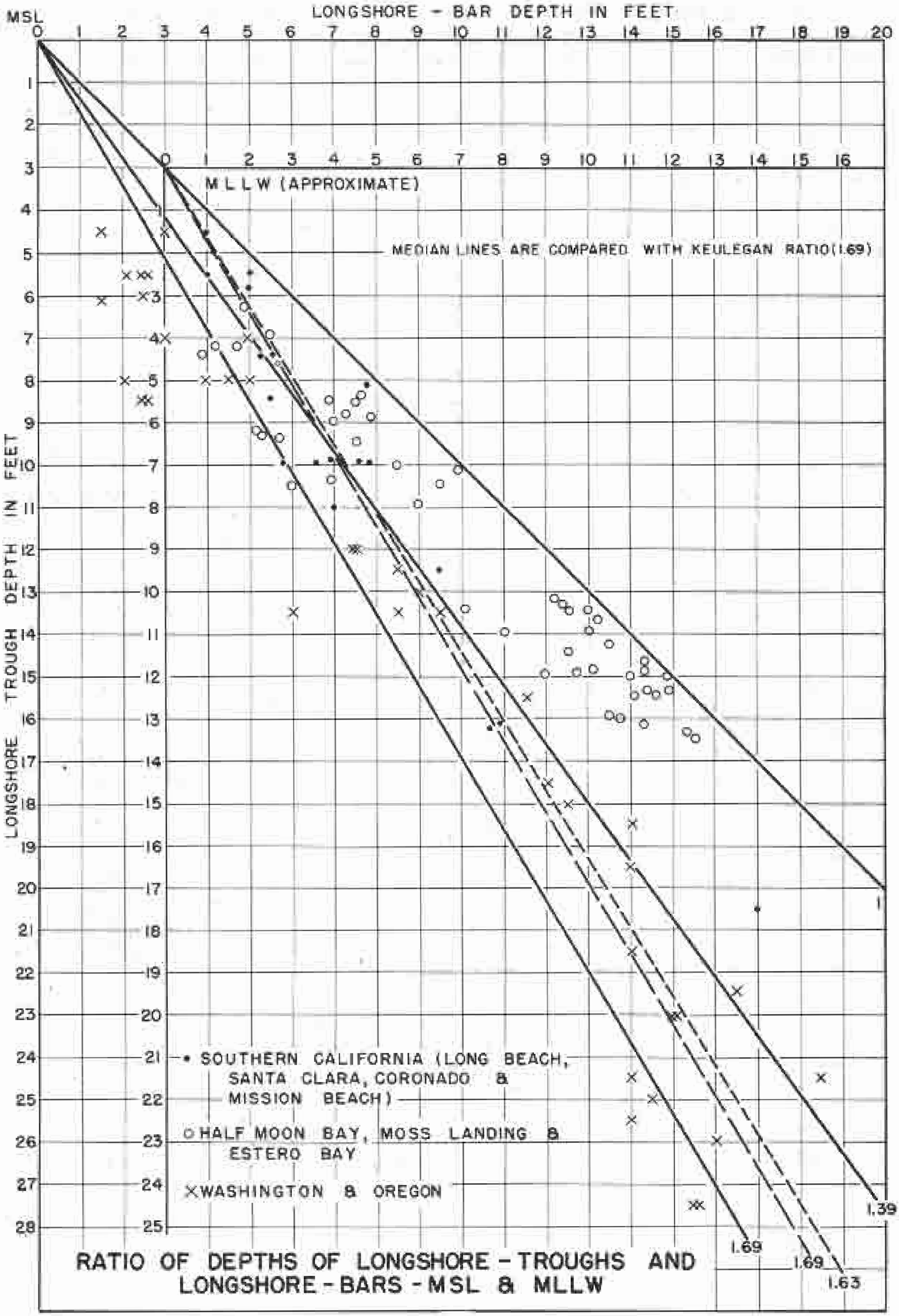
RATIO OF DEPTHS OF LONGSHORE - TROUGHS AND LONGSHORE - BARS AT SCRIPPS PIER

MEDIAN LINES ARE COMPARED WITH KEULEGAN RATIO (1.69)

FIGURE 4

Ratios of bar and trough depth are influenced by a number of variables of which the most important is the slight deepening which is found along the axis of the trough towards gaps in the bars. As a result largely of his tank experiments, Keulegan came to the conclusion that the depth of longshore-bars and longshore-troughs below still-water level showed a fairly constant relation such that the depth of the trough divided by the depth of the bar is approximately 1.69. A small number of profiles from Lake Michigan and the Baltic Sea seemed to verify his ratio. A test of the ratio was made from a much larger number of beach profiles using both mean sea level and mean lower low tide level instead of still-water level. The best reference level for this comparison is not easily determined. The rate of tidal fluctuation is small near the low and high tide marks, but it is also small between a low high and high low which are closely similar in height. The average height of the tide in the latter stage is close to mean tide (figure 14). One advantage of using mean lower low tide is that under some circumstances, particularly with large waves, the longshore-bars and longshore-troughs developed at the higher levels may be eliminated at low tide level whereas the low tide bars and troughs are likely to persist during high tides. A plot of these relations for 276 cases at Scripps pier (figure 4) shows that the mean relationship is 1.16 using mean sea level, or 1.23 using lower low tide. A much smaller number of sections along other California piers shows a relationship of 1.40 for mean sea level, or 1.63 for lower low tide, for the troughs to bars. A series of 116 profiles taken out from west coast beaches by the Engineering Department at the University of California, Berkeley, and by the Corps of Engineers, U. S. Army, gave a value of 1.39 using mean sea level, or 1.63 using lower low tide (figure 5). However, considering only the profiles reported by Isaacs (5) off Oregon and Washington, the ratio is close to that of Keulegan, being 1.60 using mean sea level, or 1.93 using lower low tide. This area is one of very large waves, 20- to 30-foot breakers being common during storms. A series of east coast profiles largely off Cape Cod (figure 6) indicate 1.34 using mean sea level, or 1.47 using mean low tide, for the average trough to bar ratio. All of these diagrams show a considerable spread in the ratio and in general indicate that the ratio decreases with depth. The ratios for mean sea level for the 4 groups average 1.3, or 1.5 for mean low water. The discrepancy with Keulegan's ratios may be explained because his sources of information were tank experiments which had bars and troughs of small amplitude.

Keulegan considered also that there was a common ratio between depths of the bar and what he called the bar base. He defined the latter as the line connecting the trough and the barless profile outside the bar. His experiments indicated that the depth of the bar had a ratio to the depth of the bar base, directly underneath the bar, of 0.58. This ratio was also tested from the beach profile. The large number of Scripps pier profiles shows the ratio for mean sea level to be 0.77. or 0.70 using lower low tide (figure 7). However, the profiles at other piers give 0.58 using mean sea level, or 0.46 using lower low tide. The west coast beach profiles give a



RATIO OF DEPTHS OF LONGSHORE - TROUGHS AND LONGSHORE - BARS - MSL & MLLW

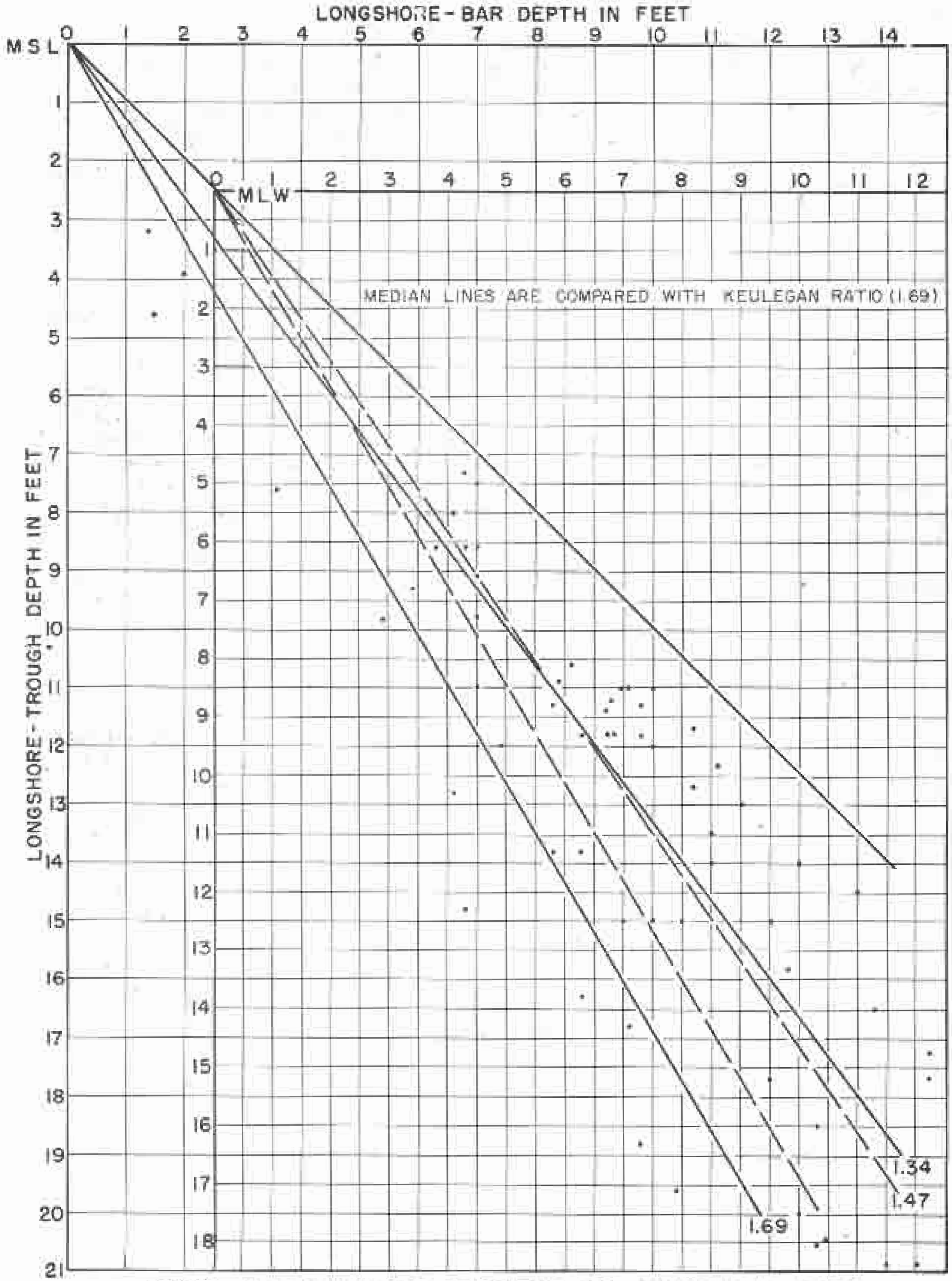
FIGURE 5

ratio of 0.63 using mean sea level, or 0.53 using lower low tide (figure 8), with distinctly higher ratios for the greater depths. The profiles off Oregon and Washington have a ratio of 0.57 using mean sea level, or 0.46 using lower low tide. The east coast sections largely off Cape Cod gave a ratio of 0.59 using mean sea level, or 0.53 using mean low tide (figure 9), also close to that of Keulegan. The average ratio for the 4 groups for mean sea level is 0.63 or 0.55 using lower low tide. Thus the Keulegan ratio for these parameters checks very well.

Relation of Bars and Troughs to Wave Height

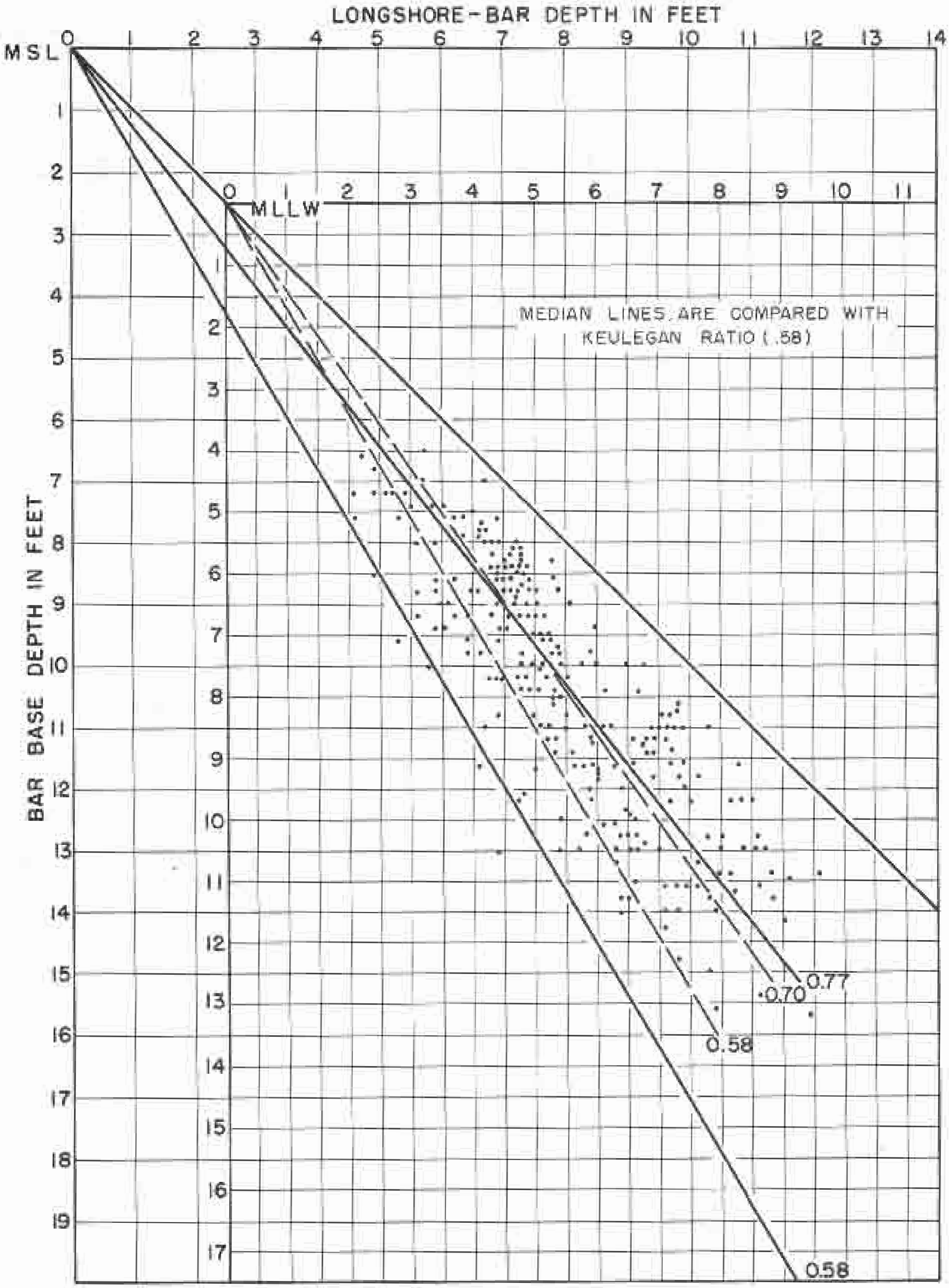
Evans, Keulegan, and King and Williams all recognized the relationship between the wave size and bar depth. This relationship becomes still more evident from the study of the profiles taken along the California piers. The most substantial data were derived from the profiles along Scripps pier (figure 10). A plotting of bar depth against the wave heights which were measured daily shows a grouping of points around the median line but having a rather large spread. The same relation comes from the plot of trough depths against wave height (figure 11). The quartile lines in figures 10 and 11 drawn parallel to the median line indicate that more than 50% of the points lie within one foot of the median line. There can be little doubt but what deeper longshore-bars and longshore-troughs are found on the days of larger waves. The relationship was also tested by plotting the greatest wave height of the preceding 5 days against the bar depth (figure 12), but this does not group the points as close to the median line as did the plotting with accompanying wave heights.

A comparison of some of the daily profiles to changing wave heights indicates the nature of changes which take place (figures 3, 13, and 18). The complete record for the 1937-38 measurements of depth changes of both the longshore-bar and longshore-trough along with wave height and bar height above the trough is given in figure 14. The fact that the response to changing wave conditions is similar throughout the years leaves little doubt of the reality of this relationship. The bars accompanying relatively small waves are cut away by the large waves and new bars from outside. However, the building up of the new bars may lag so that the first effect of a day of large waves is likely to be a cutting away of the old bar and the excavation of a deep trough inside rather than the building of a new bar on the outside. The new bar often develops after the large waves have subsided. A comparison of the wave record over the year with the cross-sectional area of the bar is also instructive (figure 15). This cross-sectional area is derived by drawing a horizontal line out from the bottom of the trough to the point where the line intersects the outer slope and computing the area of the bar above the line. The bars clearly increase in size during the season of large waves, but the increase generally lags after a particular period of large breakers. Longshore-bar and longshore-trough depths show a relationship to maximum wave heights. Thus the bar crests off southern California are



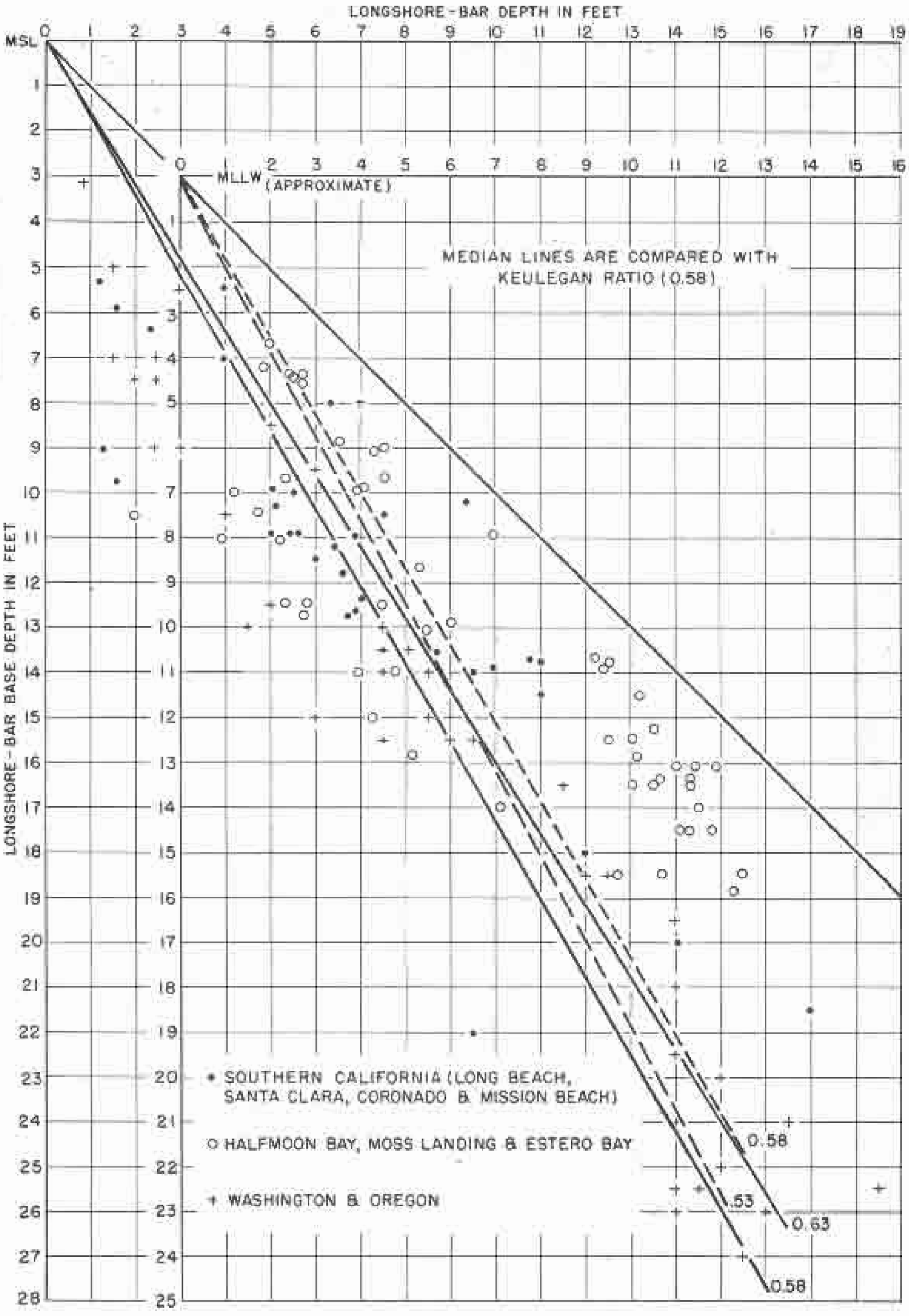
RATIO OF LONGSHORE-TROUGHS TO LONGSHORE-BARS
U.S. EAST COAST

FIGURE 6



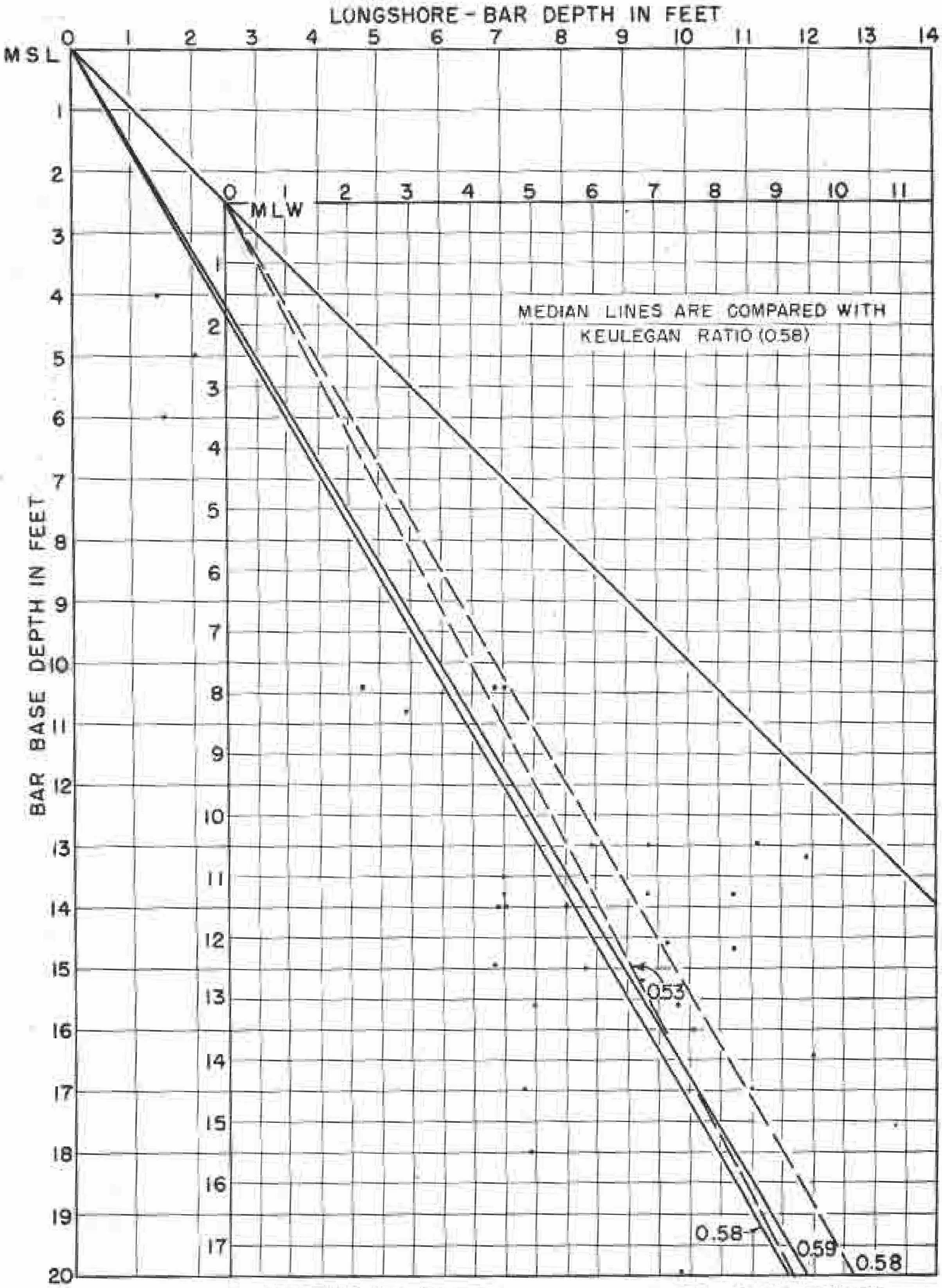
RATIO OF DEPTHS OF LONGSHORE-BARS TO
BAR BASES AT SCRIPPS PIER

FIGURE 7



RATIO OF DEPTHS OF LONGSHORE BARS TO BAR BASES—MSL & MLLW

FIGURE 8



RATIO OF DEPTHS OF LONGSHORE - BARS TO BAR BASES
U.S. EAST COAST

FIGURE 9

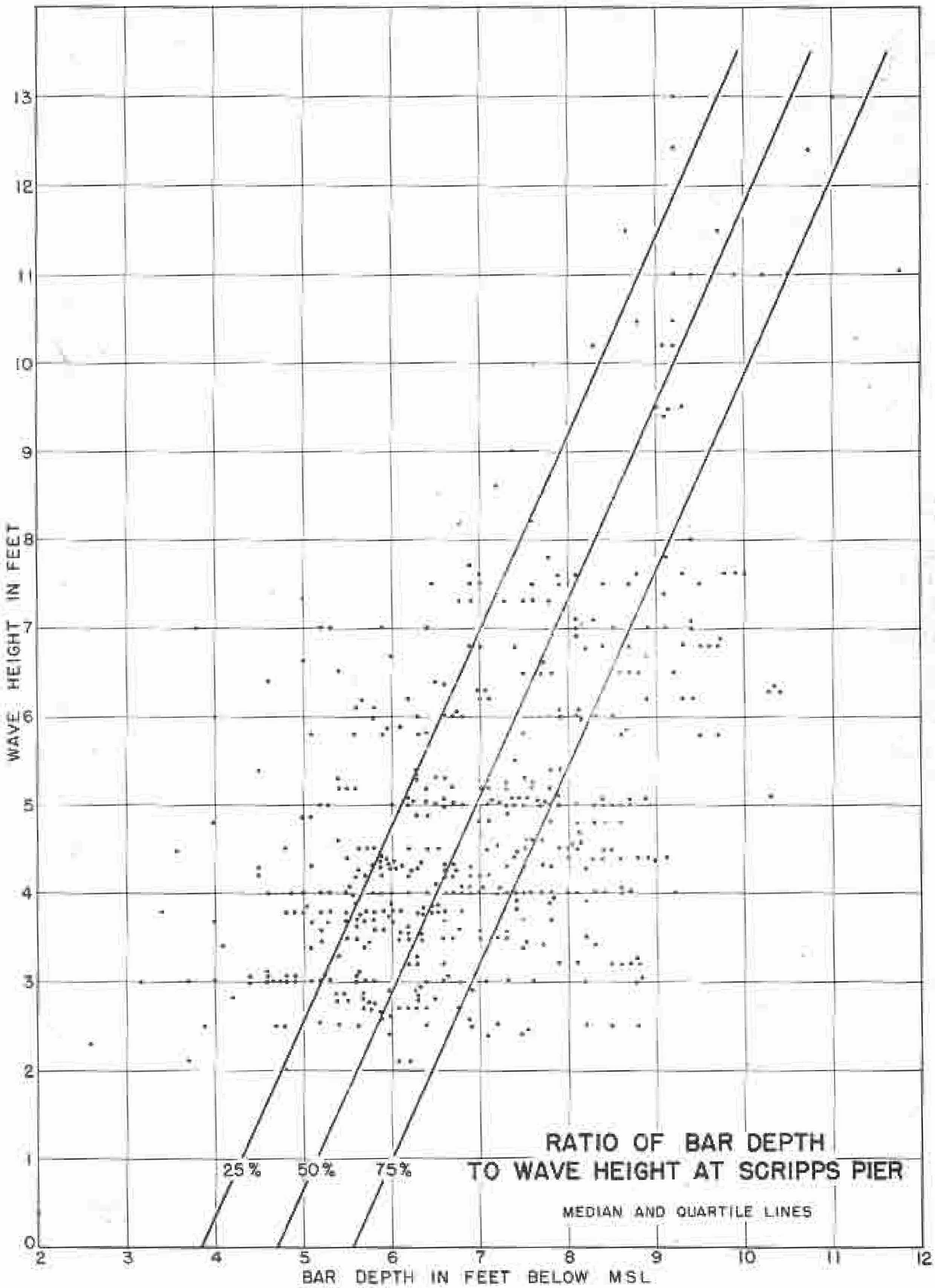

RATIO OF BAR DEPTH
TO WAVE HEIGHT AT SCRIPPS PIER
MEDIAN AND QUARTILE LINES
25%
50%
75%
WAVE HEIGHT IN FEET
BAR DEPTH IN FEET BELOW MSL
0
1
2
3
4
5
6
7
8
9
10
11
12
13

FIGURE 10

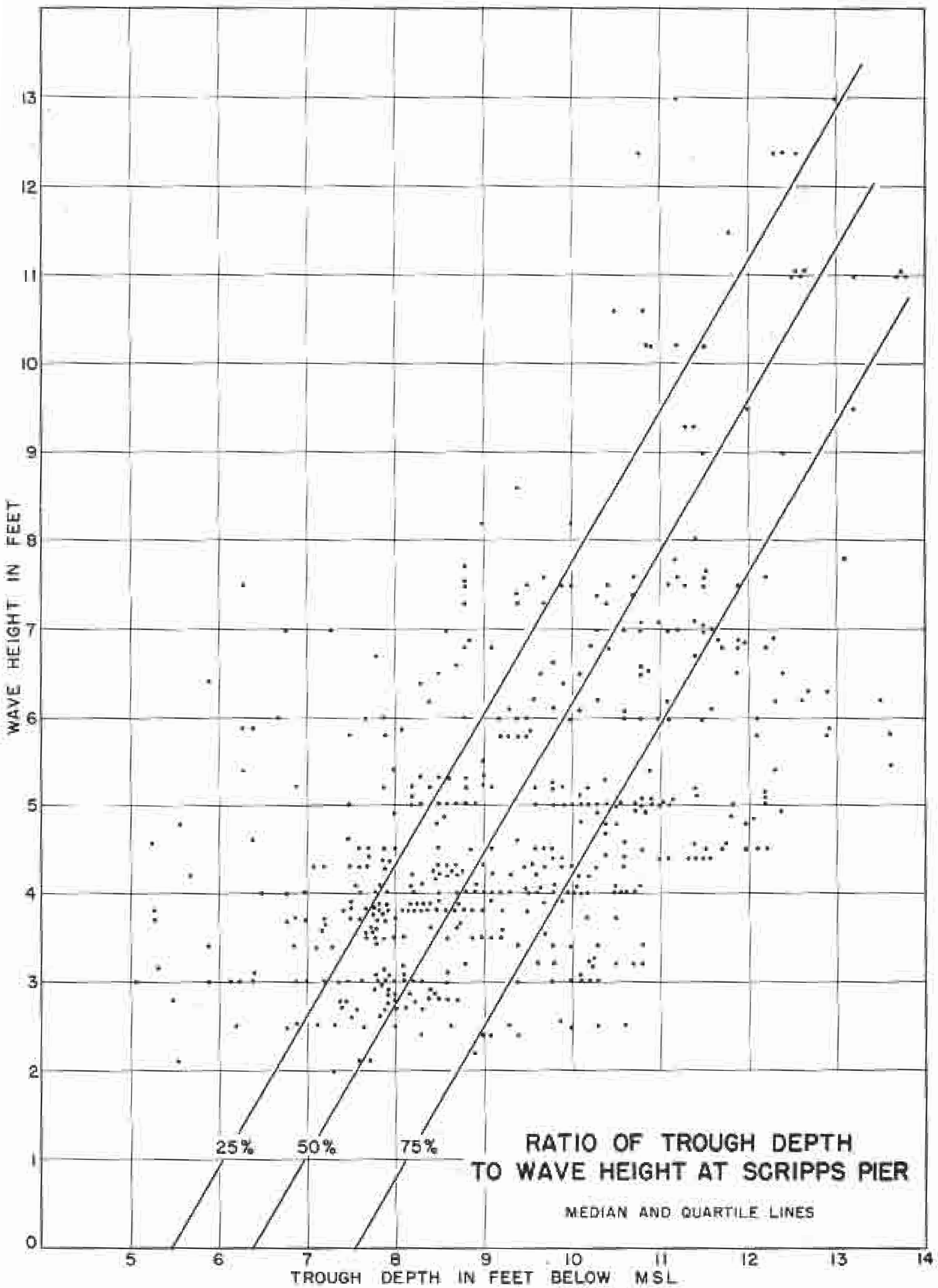

RATIO OF TROUGH DEPTH
TO WAVE HEIGHT AT SCRIPPS PIER
MEDIAN AND QUARTILE LINES
25%
50%
75%
WAVE HEIGHT IN FEET
TROUGH DEPTH IN FEET BELOW MSL

FIGURE 11

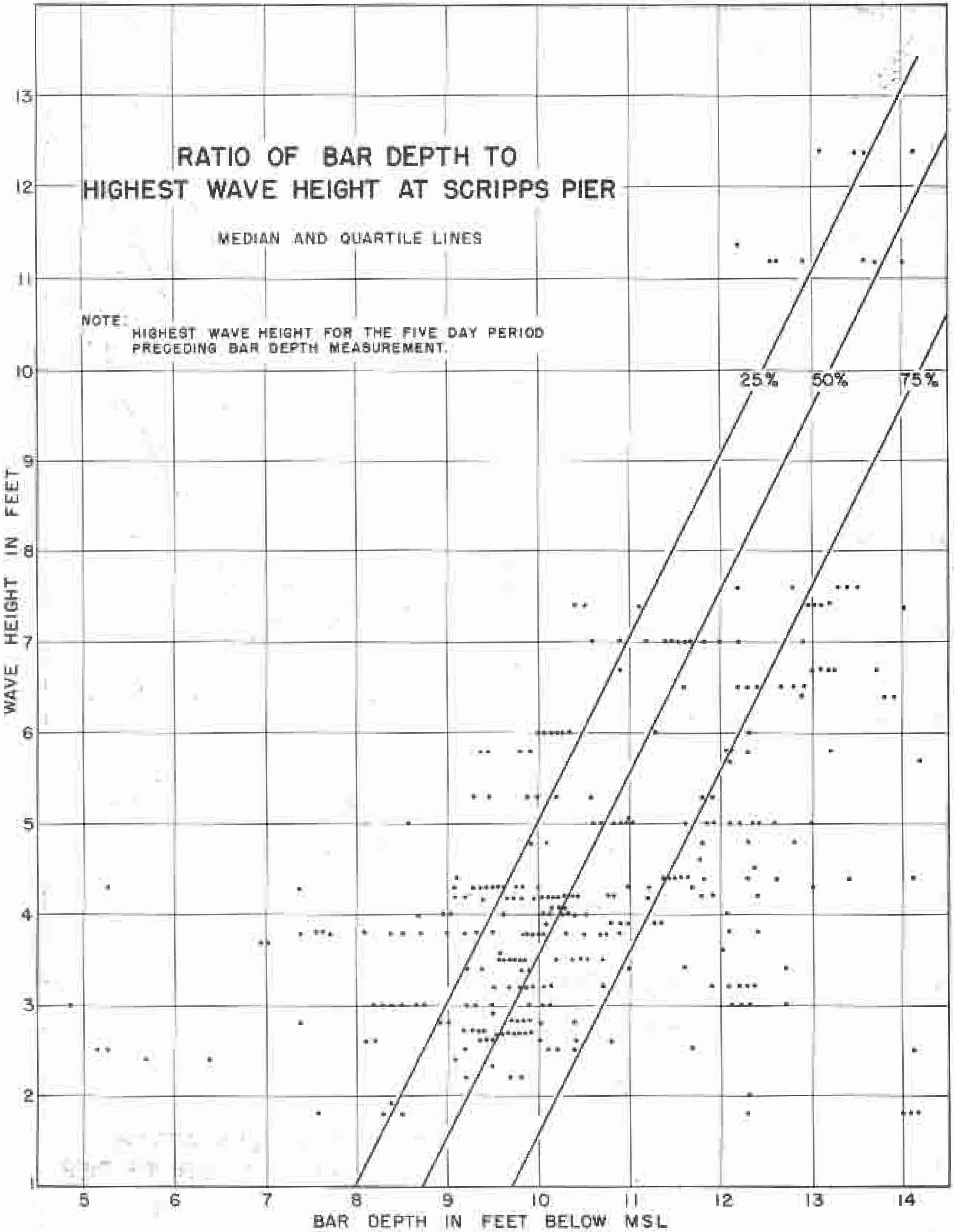
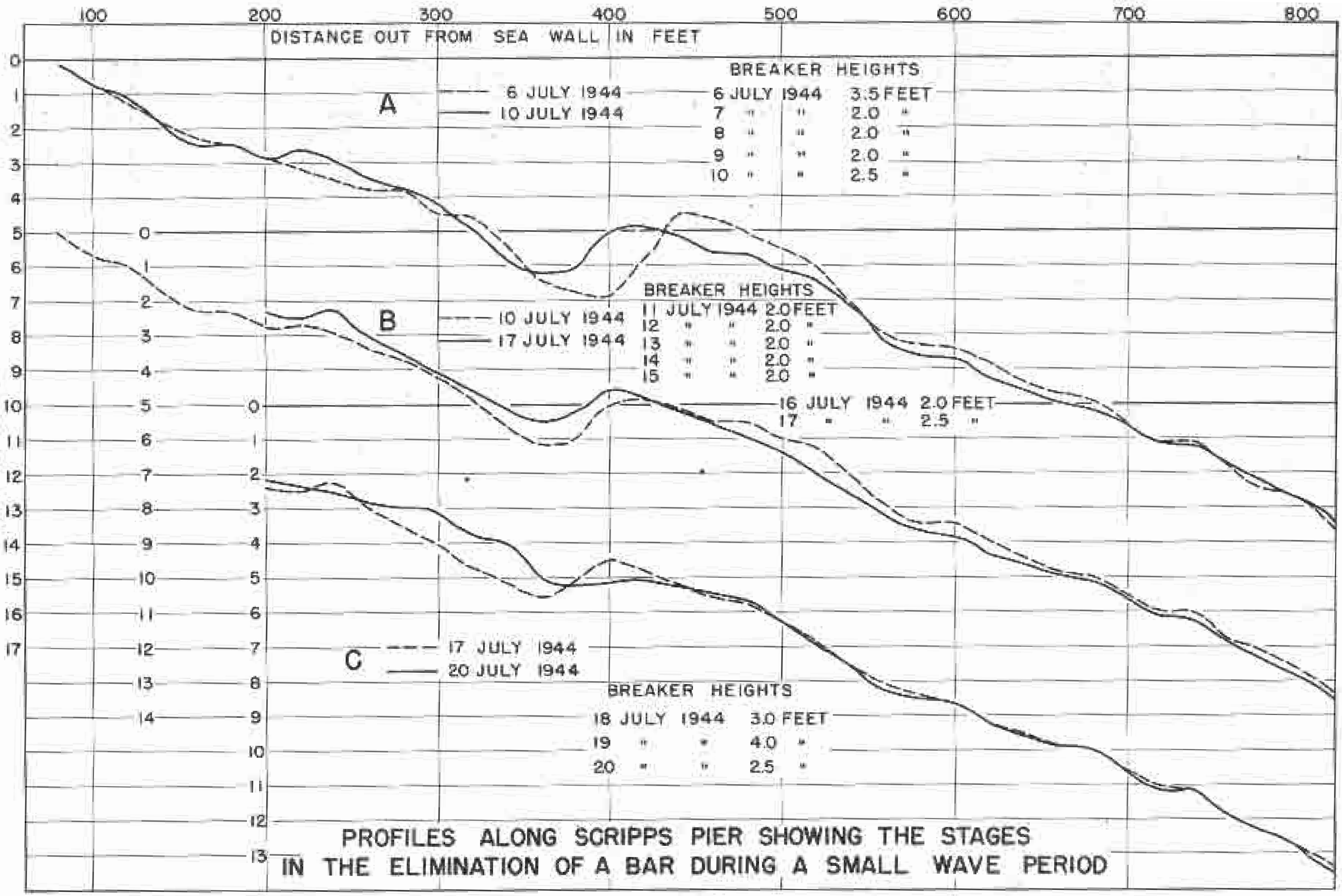

RATIO OF BAR DEPTH TO
HIGHEST WAVE HEIGHT AT SCRIPPS PIER
MEDIAN AND QUARTILE LINES
NOTE:
HIGHEST WAVE HEIGHT FOR THE FIVE DAY PERIOD
PRECEDING BAR DEPTH MEASUREMENT.
25%
50%
75%
WAVE HEIGHT IN FEET
BAR DEPTH IN FEET BELOW MSL
1
2
3
4
5
6
7
8
9
10
11
12
13
14

FIGURE 12



PROFILES ALONG SCRIPPS PIER SHOWING THE STAGES IN THE ELIMINATION OF A BAR DURING A SMALL WAVE PERIOD

FIGURE 13

almost all less than 10 feet below mean sea level. In this area breakers are rarely greater than 10 feet. Off Washington and Oregon 20-foot waves are fairly common and bars extend to depths of at least 18 feet. This difference can be seen by the groupings of points from southern California and from Washington and Oregon in figure 5.

A plotting of the bar depth at a series of piers in southern California was made in relation to the seasonal change (figure 16). All of the bars and troughs shoaled as the summer period of small waves advanced. A similar effect over a much longer period is shown by the depth of the bars and troughs along the Scripps pier during a 8-year period (figure 17).

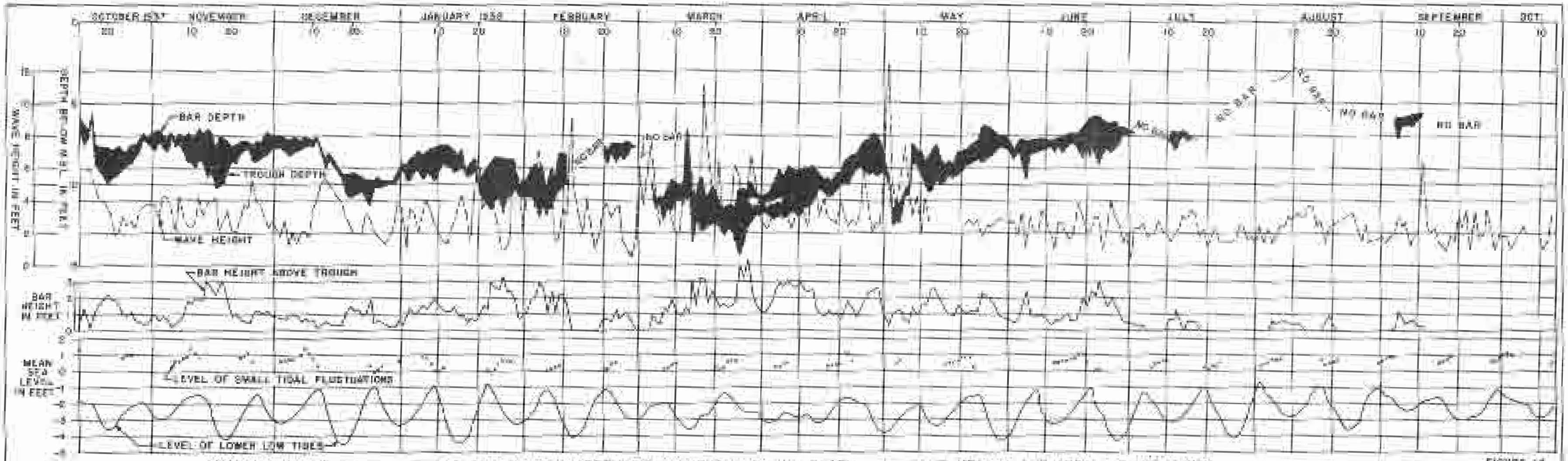
Relation to Currents

The data do not permit as good a correlation between longshore-bar and longshore-trough development and currents as is possible with wave height. Currents were observed but not measured at several points along the Scripps pier during most of the period of daily sand measurement, and a Sverdrup-Dahl current meter was in use at the end of the pier during most of the time. It is unfortunate that there is not a complete record of currents in the zone of bar and trough development. However, out of 98 observations in this zone only 9 showed currents in a different direction from the currents observed at the pier end at the same time. There appear to be some striking relations between the area of the longshore-bar and the current direction (figure 15). South currents apparently increase the area of the bar and the strongest recorded south current was observed just before the bar grew to its largest area. North currents conversely appear to have the effect of decreasing the bar area. One case where large waves were accompanied by excessive fill took place in February, 1938, during a period of north currents (figure 18, A).

A profile obtained at Oceanside pier at a time of very large longshore currents inside the breakers indicated a very large bar and trough. Other evidence suggesting that strong currents are an important factor, at least in the formation of troughs, comes from the finding of deep troughs along the path of the longshore feeder currents to rip currents during times when the currents are particularly strong (13, pp. 350-352). When these channels are exposed by low tide, current ripples are found in them indicating flow along their axes (5). Isaacs reports that these ripples increase in magnitude along the troughs towards the rip channels which cross the bars. Near these cross channels he found giant ripples similar to those in tidal channels.

Relation to Tides

The longshore-bars and longshore-troughs are necessarily dependent on the tides since waves break farther out on the offshore slope during low tides than during high tides. The large range during spring tides



CHANGES IN THE LONGSHORE-BAR AND TROUGH DEPTHS AT SCRIPPS PIER IN RELATION TO WAVE HEIGHT AND TIDAL FLUCTUATION

FIGURE 14

cause a shifting of position of deposition and cutting. This was clearly shown during a 36-hour period of continuous profile measurement. The result of this shift should be a greater development of bars and troughs during or shortly after neap tides when the breaker line remains more constant in position. A similar effect comes from the small ranges between the contiguous low high and high low which accompany neap tides.

Examination of the bar development during 1937-38 shows that other influences such as wave height and current variation are more important than tide, but there is a rough correlation between the larger bars and neap tide periods (figure 14). The first of the records showed somewhat of an inverse ratio to tide stage because of the development of large waves at spring tide, but the more typical relationship is seen during most of the year when the bars are developed best during or shortly after neap tides. It will be noted in figure 14 that the growth of the bars is also somewhat dependent on the small fluctuations between high low and low high tides.

Origin of Longshore-bars and Longshore-troughs

Speculation concerning the origin of longshore-bars has been appearing in print for more than a century. De Beaumont (1) first recognized these bars as a natural result of the readjustment of submarine slopes to existing wave conditions. He considered that wave action removed material from the sea floor and built it up as a bar parallel to the shore. Johnson (6) supported this hypothesis as the early stage in the origin of the emergent offshore bars. The present investigation, however, supports Evans (2, p. 510) in the indication that longshore-bars are in equilibrium with wave conditions and that the migration of the bars is only a temporary or seasonal fluctuation and does not form the broad emergent beaches to which the name offshore bar is applied.

Russell (12) and Gilbert (3) concluded from their studies of the longshore-bars of the Great Lakes that the materials of the bars were derived from the beaches and carried along the shore until deposited where the "undertow" loses its force. Evans (2, p. 503) supporting Johnson gave the following arguments against the origin by longshore currents:

"1. Because of the acute angle at which the inner ball (longshore-bar) usually joins the shore

2. Because the ball (longshore-bar) does not receive any considerable amount of material from the locality where it joins the shore

3. Because of the failure of the ball (longshore-bar) to build above the water as does a spit or bar (bay bar)

4. Because of the lack of any considerable connection between the outer balls (longshore-bars) and the shore, although they are generally higher above the bottom and broader than ball No. 1 (innermost longshore-bar)

5. Because the line of the bottom of the lows (longshore-troughs) prolonged intersects the surface landward rather than seaward of the shore line."

The fifth point is significant since it indicates that erosion of the sea floor rather than simple deposition has taken place. However, it does not exclude longshore currents from an important part in the production of the longshore-bars. The other points depend on the assumption that longshore drift builds only structures which extend to the surface, such as spits, bay bars, and offshore bars. Actually there is no proof that this is the case.

One can agree better with Evans' suggestion (2, p. 508) that the longshore-troughs are the result of plunging breakers. However, his conclusion that the material set in suspension is carried out to form the bar may be only partially correct because the profiles along Scripps pier indicate that in many cases the material has come from the outside. Keulegan (7, figure 4) established through his experiments that the trough position is determined by the position of the plunging breaker. King and Williams (9, p. 80) considered that the bar forms at the "break point" as the result of seaward movement of material inside and landward on the outside.

The investigations at Scripps Institution do not offer any radically different hypothesis for the origin of the longshore-bars and longshore-troughs. The importance of the plunging of breakers is indicated by the close correspondence of the longshore-bar crest depths with the wave height. The waves steepen and start to break onto the bar and then plunge into the trough on the shoreward side of the bar. The position of the longshore-bar and longshore-trough is somewhat a matter of chance since given an even slope the position at which a series of newly developed large waves will break is dependent on the state of the tide when these waves begin their work. Many of the troughs may be initiated by the coincidence of several plunging waves along approximately the same line. Once developed the trough is likely to continue. Further indication of the importance of wave plunging in forming troughs and bars comes from the discovery that spilling waves such as accompany short-period storm waves with high local winds tend to obliterate longshore-bars. Under these conditions the longshore-bars and longshore-troughs at Scripps pier have been completely eliminated (figure 3, C) presumably because there was no breaker line. The inner longshore-bars and longshore-troughs are commonly destroyed by storm waves where the wind-driven waves break without plunging and no second set of breakers can be developed. This was nicely demonstrated by the effects of a northeast sorm which locally attained hurricane velocities along the outer side of Cape Cod, Massachusetts (figure 19).

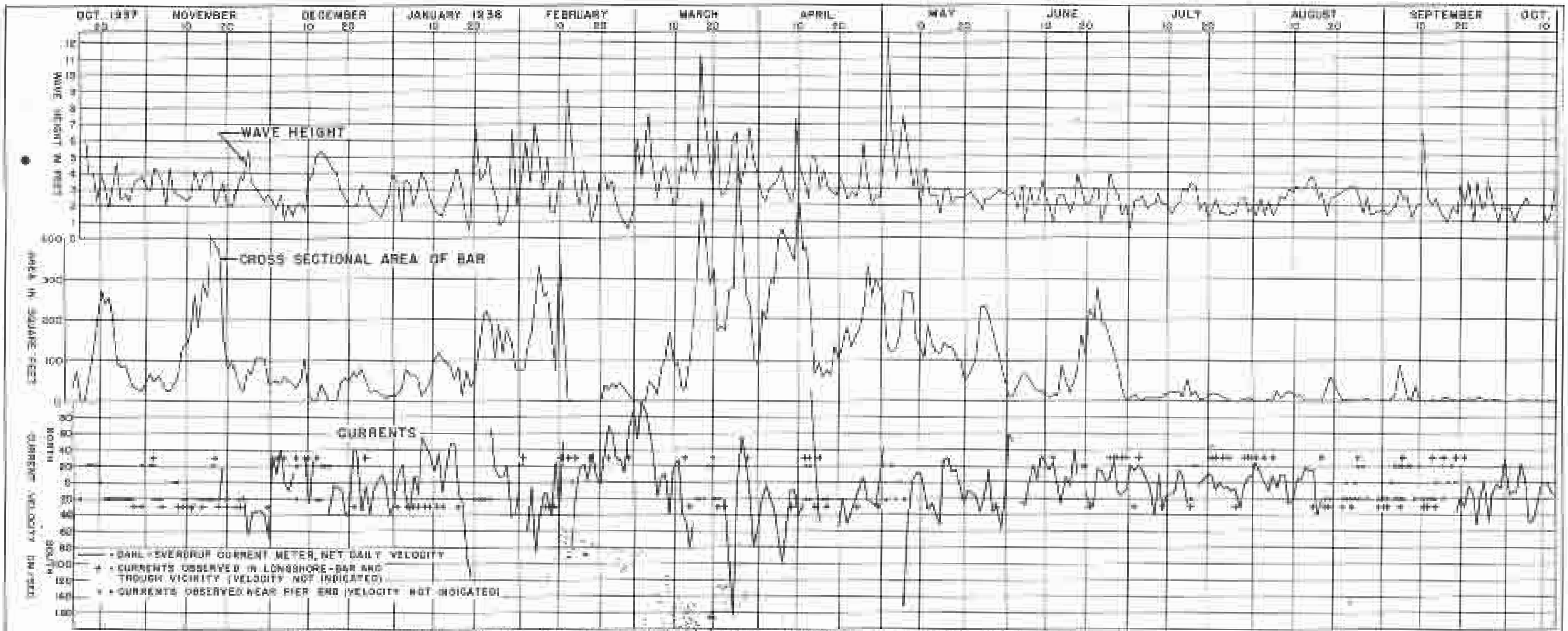
Longshore currents have an important influence in the development of longshore-troughs. The slight net seaward transport which is observed along the bottom inside the breakers tends to concentrate the bottom water in the longitudinal depressions produced by the plunging waves, resulting in a strong flow parallel to the shore. These currents become feeders to the rip currents which break seaward through the bar at various points (13). The channels along these feeder currents may be exposed at low tide. Isaacs found that the rippled inner troughs partially exposed by low tide deepened progressively towards a point where they connected with a passage leading through the bar (a rip channel).

According to measurements made by Scripps Institution groups along the southern California coast, the rip currents become concentrated in the surface layers outside the breakers with the result that there is no very definite indication of a seaward net transport of water along the bottom. Since shoreward velocities under wave crests are somewhat in excess of the seaward velocity under wave troughs, sediment tends to move shoreward along the bottom unless the slope is so steep that the gravitative effect will counteract this movement up the slope. The shoreward movement is of course most effective near the breaker line in the relatively shallow water where the wave effect is most vigorous.

If the wave height and the water level should remain essentially the same, a profile of equilibrium will result because the shoreward movement of the sand will build the bar up only to the height where waves will break on top of it with sufficient force to carry away the sand which is being added. Similarly the trough will continue to deepen only to the depth at which the bottom current is capable of carrying away the sand contributed to it both from the landward migrating bar outside the breakers and from the seaward transport of material inside the breakers.

If the wave height changes, the equilibrium will be disturbed. If the waves are larger (assuming the same period) the breakers will plunge on top of the bar and thus cut it away (figure 18, B) and after a time a new bar will develop seaward of the old (figure 18, C). In the early stages of large waves the cutting effect is the most significant but the sediment which is largely carried out in the rip channels will tend to be redistributed along the outer slope and start moving in to build up the bars at depths which are compatible with the new wave height. The few instances where deposition took place along Scripps pier during large waves are not clearly understood, but they are apparently the result of the reversal of current which caused a blocking of the natural outlets of the troughs and thereby caused an accumulation of the sediment against the pier.

Lowered wave height will allow the bar to grow shoaler and to encroach onto the trough as in figure 13, A-C. If the feeder currents are no longer capable of maintaining the trough in its deep position because of the shoreward movement of the breaker zone, the trough



VARIATION IN THE CROSS-SECTIONAL AREA OF THE LONGSHORE-BAR AT SCRIPPS PIER IN RELATION TO WAVE HEIGHT AND NEARSHORE CURRENTS

FIGURE 15

SEASONAL CHANGES OF LONGSHORE—BARS

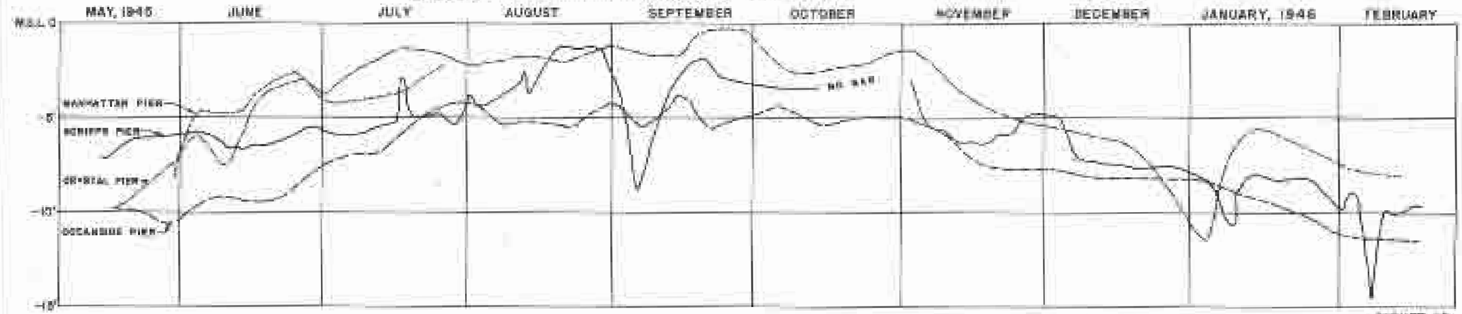


FIGURE 16

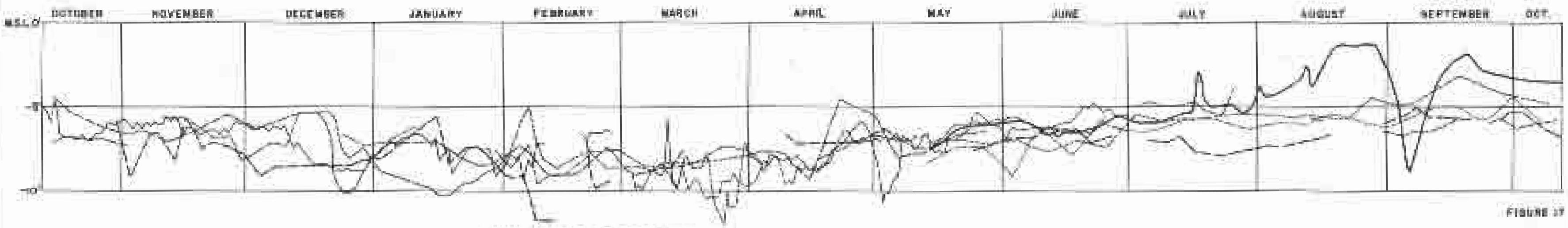
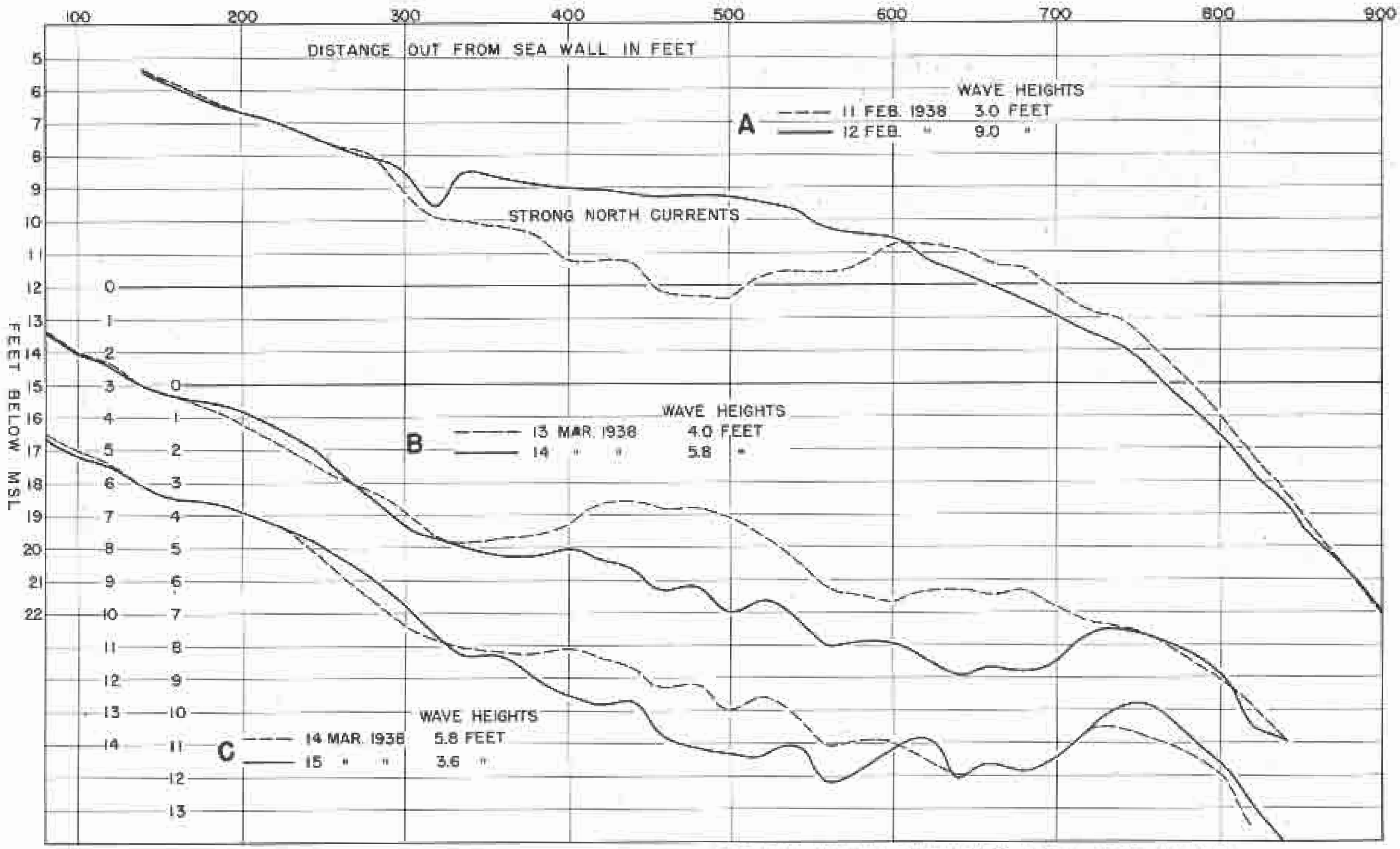


FIGURE 17

EIGHT YEARS OF SEASONAL CHANGES OF LONGSHORE-BAR AT SCRIPPS PIER



A-PROFILE CHANGES AT SCRIPPS PIER DURING STRONG NORTH CURRENTS AND LARGE WAVES
B-EXCAVATION AT SCRIPPS PIER DURING INCREASED WAVE HEIGHT
C-BUILDING UP OF BAR OUTSIDE AT SCRIPPS PIER DURING DECREASED WAVE HEIGHT

FIGURE 18

will fill and the slope become relatively even in the zone where the bar and trough had existed previously.

During periods of large waves the development of multiple longshore-bars is readily explained as the result of the re-forming of the waves over the troughs after breaking on the outer bar (figure 2). In shoaler water the wave breaks again with an exact repetition of the bar and trough forming process. Since the waves are smaller the topographic relief of the inner bars and troughs is less striking. Other cases of multiple bar development can be explained by a rising tide causing the waves to break at successively higher points along the slope. Wherever a good development of rip feeder currents is capable of carrying the sediment away from the plunge zone a trough will tend to develop. A falling tide, however, will tend to destroy the shoaler bars, as was shown in the tank experiments by King and Williams (9, p. 81). Longshore-bars and longshore-troughs developed by large waves may not be destroyed when the waves decrease and new bars and troughs are developed at shoaler depth. King and Williams developed two sets of bars in their tank experiments by decreasing the wave size. Isaacs found that during the small wave season he could anchor a wave meter on a deep outer bar off the Oregon coast and it remained undisturbed. These deep bars are the product of large winter waves.

The general absence of significant longshore-bars off steep beaches is readily explained by the fact that the waves break so close to the shore that there is no opportunity for the development of the longshore currents along the plunge zone. The association of well-developed cusps with these steep beaches is probably of some significance in this connection.

Summary and Conclusions

Slightly submerged sand bars extend parallel to the shore line off most gently sloping beaches. Hundreds of profiles of longshore-bars have been taken largely along the west coast. An analysis of these profiles has shown that there is considerable variation in the relation between depth of trough and depth of bar below mean sea level. The most representative relation shows that the troughs are 1.3 times as deep as the bars with reference to mean sea level, or 1.5 times as deep with reference to mean lower low water. The depth ratio between bar crest and bar base is 0.61 for mean sea level, or 0.55 for mean lower low water, which compares well with the 0.58 ratio indicated by Keulegan's experiments at the Beach Erosion Board laboratory. A source of difficulty in developing such ratios comes from the deepening of the longshore-troughs towards gaps in the longshore-bars.

The depth of the longshore-bars was found to be related to the height of waves and to the position of breakers. Plunging breakers excavate the bottom, producing the longshore-troughs. The material thus set into suspension is moved parallel to the shore by currents which turn seaward into rip channels forming gaps in the longshore-bars. Some of the bars and troughs are exposed by low tide. The

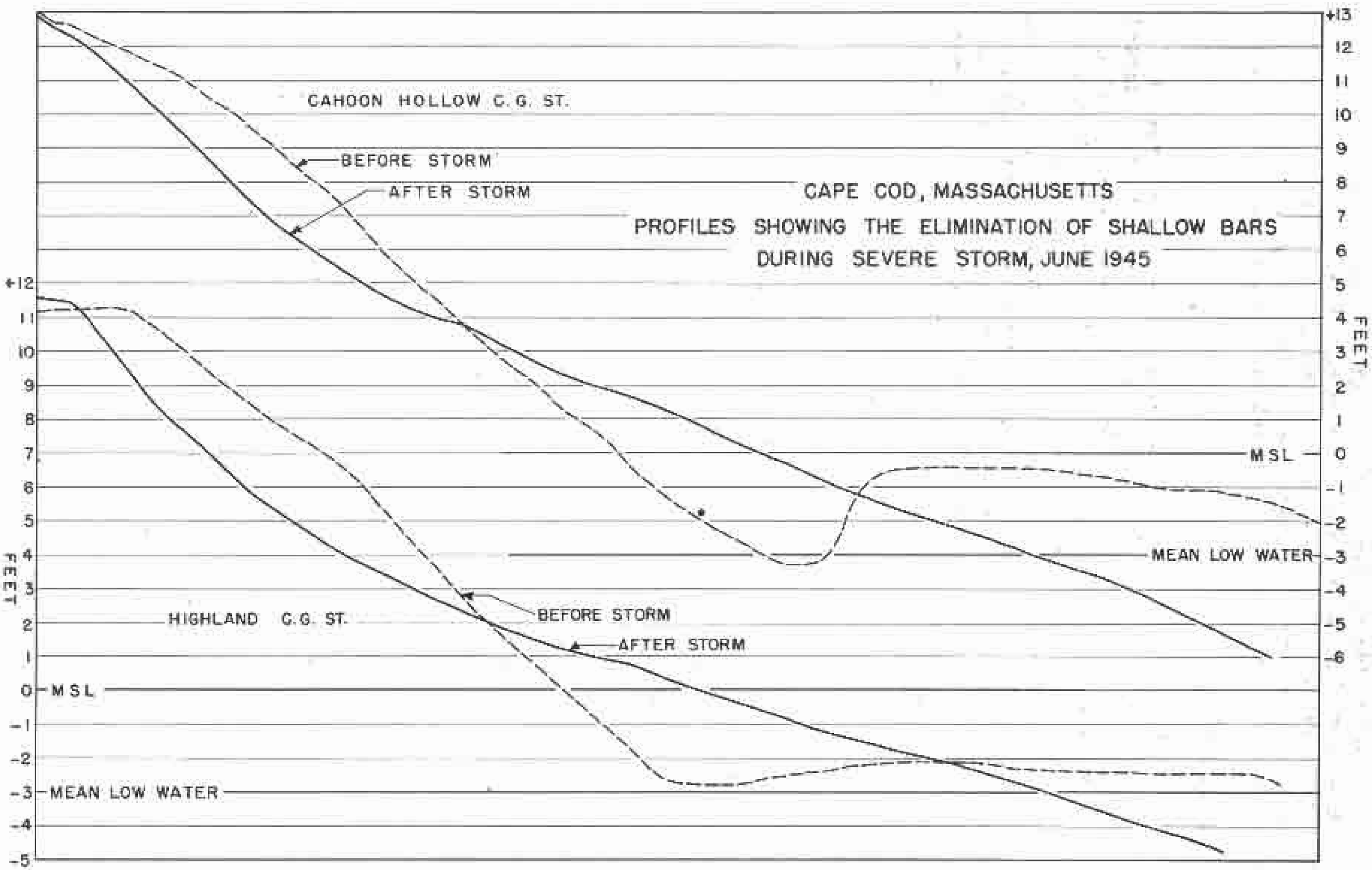

CAPE COD, MASSACHUSETTS
PROFILES SHOWING THE ELIMINATION OF SHALLOW BARS
DURING SEVERE STORM, JUNE 1945
CAHOON HOLLOW C. G. ST.
BEFORE STORM
AFTER STORM
HIGHLAND C. G. ST.
BEFORE STORM
AFTER STORM
M S L
MEAN LOW WATER
M S L
MEAN LOW WATER
FEET
FEET
+12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
+13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6

FIGURE 19

sand carried outside the bar is spread out over the slope by the expanding head of the rip current. Thence the shoreward drag under wave crests carries it back to build up the longshore-bars outside the troughs. The growth of these bars is limited by the depth at which the waves will plunge and prevent further sand encroachment.

Acknowledgments

The assistance received from U. S. Navy projects has been referred to previously. Expecial gratitude is expressed to E. C. LaFond who took many of the profiles along the piers, supervised the taking of a large part of the remainder, and was also a large contributor to determining the relations of the longshore-bars to the waves and currents. Much important information was contributed by John D. Isaacs from his extensive investigations of beaches along the west coast. Helpful suggestions were also provided by D. L. Inman and R. S. Arthur. Others who have taken an active part in the work include D. B. Sayner, Ruth Young, K. D. Langley, Ralph Gentoff, Mrs. Rosemarie Snow, and Mrs. Dorothy Williams.

REFERENCES

(1) Beaumont, E. de. 1845. "Lecons de Geologie Pratique." 557 pp. Paris.

(2) Evans, O. F. 1940. "The low and ball of the eastern shore of Lake Michigan." Jour. of Geol., Vol. XLVIII, pp. 476-511.

(3) Gilbert, G. K. 1890. "Lake Bonneville," U.S. Geol. Surv. Mono. I, p. 44.

(4) Isaacs, J. D. 1945. "A device for traversing the surf zone of ocean beaches.", Univ of Calif., Fluid Mech. Lab., Tech. Rpt. 90 (a).

(5) Isaacs, J. D. 1947. "Beach and surf conditions on beaches of the Oregon and Washington coast between August 27 and September 27, 1945." Univ. of Calif., Fluid Mech. Lab. Memo. HE-116-229.

(6) Johnson, D. W. 1919. "Shore processes and shore line development." 584 pp.

(7) Keulegan, G. H. 1948. "An experimental study of submarine sand bars." Beach Erosion Board, Office of the Chief of Engineers, Tech. Rpt. No. 3.

(8) Kindle, E. M. 1936. "Notes on shallow-water sand structures." Jour. Geol. Vol. XLIV, No. 7, pp 861-869.

(9) King, C. A. M., and Williams, W. W. 1949. "The formation of sand bars by wave action." Geog. Jour., Vol. CXIII, pp. 70-85.

(10) Otto, Theodor, 1911-12. "Der darss und zingst." Jahrb. d. Geog. Gesell. zu Greifswald, Band XIII, pp. 393-403.

(11) Passarge, Seigfred, 1912. "Physiologische morphologie," Mitt.d. Geog. Gesell. in Hamburg, pp. 195-198.

(12) Russell, I. C. 1885. "Geological survey of Lake Lahontan." U.S. Geol. Surv. Mono. II, pp. 92-93.

(13) Shepard, F. P., Emery, K. O. and LaFond, E. C. 1941. "Rip currents; a process of geological importance." Jour. Geol., Vol. 49, pp. 337-369.

(14) Shepard, F. P., LaFond, E. C., 1940. "Sand movements along the Scripps Institution pier, California." Am. Jour. Sci., Vol. 238, pp. 272-285.

(15) U. S. Coast and Geodetic Survey, 1890. "Cross sections of the ocean shore of Cape Cod." Appendix No. 13 for the Report for 1889.

(16) Veatch, A. C., and Smith, P. A. 1939. "Atlantic submarine valleys of the United States and Congo submarine valley." Geol. Soc. Am., Special Paper No. 7.